UNIVERSIDADE FEDERAL DO PAMPA

MILENA AGUIAR DOS SANTOS

EFFECTS OF TRICEPS SURAE EXERCISE-INDUCED DELAYED ONSET MUSCLE SORENESS ON CONTROL OF BODY STABILITY IN DIFFERENT POSTURES

Uruguaiana
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A Dissertation presented to the Multicenter Graduate Program in Physiological Sciences from Universidade Federal do Pampa, as a partial requirement for the degree of Master in Physiological Sciences

Supervisor: Prof. Dr. Felipe Pivetta Carpes

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EFEITOS DA DOR MUSCULAR TARDIA NO TRICEPS SURAL INDUZIDA PELO EXERCÍCIO SOBRE O CONTROLE DA ESTABILIDADE EM DIFERENTES POSTURAS

Dissertação de Mestrado apresentada ao Programa de Pós-graduação Multicêntrico em Ciências Fisiológicas da Universidade Federal do Pampa como requisito parcial para o título de Mestra em Ciências Fisiológicas.

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I dedicate this work to all the people who have crossed paths with me, those who have stayed, and those who will come.

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“There are many hypotheses in science that are wrong. That is perfectly all right; it is the gap to finding out what is right. Science is a self-correcting process. To be accepted, new ideas must survive the most rigorous standards of evidence and scrutiny.”

(Carl Sagan, Cosmos)

ABSTRACT

A common strategy to manipulate exercise intensity for strength gains is to select exercises requiring eccentric muscle actions. These exercises are common, for example, for the training and rehabilitation of the triceps surae muscles. However, this context is also known to cause delayed onset muscle soreness (DOMS). DOMS in the triceps sural can have negative repercussions on the performance of daily life tasks. Although the acute effects of triceps sural fatigue are addressed in previous studies, there is still little evidence on the effects of triceps sural DOMS on postural control. In this study, we determined whether triceps sural DOMS affects stability in unipedal bipedal postural control tasks. Participate in this study 24 subjects with (mean ± standard deviation) age of 23.8 ± 3.69 years, body mass of 68.65 ± 12.67 kg, and height of 1.69 ± 0.08 m, assessed on two days. On the first day, demographic data were collected, and the presence of triceps sural pain (through a numerical scale and pressure pain threshold), and postural control during bipedal and unipedal standing and unipedal landing tasks (through a force platform and calculation of the center of pressure and stabilization time) were assessed. Next, they completed a protocol to induce DOMS in the triceps sural (heel raise exercise to exhaustion). On the second day, 48 h after DOMS induction, DOMS was assessed using the numerical scale and pressure pain threshold and postural control during standing and landing tasks. DOMS and postural control results were compared between days. DOMS in the triceps sural was observed 48 h after its induction and led to increased mediolateral displacement of the center of pressure in standing postural control tasks. However, the presence of DOMS did not seem to induce differences in time to stabilization in unilateral landing tasks. In conclusion, exercise-induced muscle soreness in the triceps sural led to impaired control of the mediolateral component of the center of pressure during postural tasks. This highlights the importance of evaluating and adapting training and rehabilitation sessions, considering individual differences in task difficulty and strategies used by participants for posture control.

Keywords: postural control; fatigue; muscle pain; stability

RESUMO

Uma estratégia comum para manipular a intensidade do exercício físico visando ganhos de força é selecionar exercícios requerendo ações musculares excêntricas. Estes exercícios são comuns, por exemplo, para o treinamento e reabilitação dos músculos do tríceps sural. No entanto, este contexto também é conhecido por causar dor muscular de início tardio (DMIT). A DMIT no tríceps sural pode ter repercussões negativas no desempenho de tarefas da vida diária. Embora os efeitos agudos da fadiga do tríceps sural sejam abordados em estudos prévios, ainda há poucas evidências sobre os efeitos da DMIT do tríceps sural no controle postural. Neste estudo, determinamos se a DMIT do tríceps sural afeta a estabilidade em tarefas de controle postural unipodal e bipodal. Participaram deste estudo 24 indivíduos com (média ± desvio padrão) idade de 23.8 ± 3.69 anos, massa corporal de 68.65 ± 12.67 kg e estatura de 1.69 ± 0.08 m, que foram avaliados em dois dias. No primeiro dia, foram coletados dados demográficos, e avaliada a presença de dor no tríceps sural (através de uma escala numérica e do limiar de dor por pressão), e o controle postural durante tarefas de postura bipodal e unipodal em pé e de aterrissagem unipodal (através de uma plataforma de força e cálculo das variáveis de centro de pressão e tempo de estabilização). A seguir, eles completaram um protocolo para induzir DMIT no tríceps sural (exercício de elevação do calcanhar até exaustão). No segundo dia, 48 h após a indução da DMIT, a DMIT foi avaliada através da escala numérica e do limiar de dor por pressão e o controle postural durante tarefas de postura em pé e de aterrissagem. Os resultados da DMIT e controle postural foram comparados entre os dias. A DMIT no tríceps sural foi observada 48 h após a sua indução e acarretou aumento no deslocamento mediolateral do centro de pressão em tarefas de estabilidade da postura em pé. Contudo, a presença de DMIT não pareceu induzir diferenças no tempo de estabilização para a tarefa de aterrissagem unilateral. Em conclusão, a dor muscular induzida pelo exercício no tríceps sural levou a um controle prejudicado do componente mediolateral do centro de pressão durante tarefas posturais. Isso destaca a importância de avaliar e adaptar sessões de treinamento e reabilitação, levando em consideração as diferenças individuais na dificuldade da tarefa e nas estratégias utilizadas pelos participantes para o controle de posturas.

Palavras-chave: controle postural; fadiga; dor muscular; estabilidade

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LIST OF ABBREVIATIONS

DOMS – delayed onset muscle soreness
CoP – center of pressure
LoS – limit of anterior stability
PPT – pressure pain threshold
TTS – time to stabilization

SUMMARY

1. INTRODUCTION

Physical exercise is a fundamental part of strategic planning for maintaining long-term quality of life and independence in daily life activities. However, physical exercise can also have acute effects in both physical training and rehabilitation contexts. Some of these acute effects end up leading to transient conditions that can impair specific motor responses, which is the case of muscle soreness. In this research, we addressed the acute and short-term effects of intense physical exercise leading to acute fatigue and delayed onset muscle soreness (DOMS) on the performance of motor tasks involving postural control during upright standing and landing. We specifically studied such effects by inducing fatigue and DOMS in the triceps sural muscle group, which is an essential muscle group for postural stability during upright posture and landing tasks.

Therefore, this document is organized to report our experiments and the main results found. We initially provide a background of this topic based on a general overview of the relevant literature, followed by the rationale for establishing our research question. Finally, the material and methods are detailed, before our results and discussions are presented.

1.1 BACKGROUND

The regulation of body posture requires integrating information obtained by different systems organized in a hierarchical and parallel manner. From the lowest level, the spinal cord receives and processes somatosensory inputs, while at the highest level, the cerebral cortex takes care of more complex tasks by integrating and programming the course of action (1). Considering movement control involving posture maintenance, such as standing, stability plays an essential role by balancing stabilizing and destabilizing forces. This control requires continuous processing of information about external forces and muscle forces producing joint torques, also requiring high processing speed. Therefore, spinal reflexes and the availability of sensory information from proprioceptive receptors such as muscle spindle, Golgi tendon organ, and joint and skin mechanoreceptors are critical to enabling some automated responses (2). These mechanisms assist the central nervous system (CNS) in generating postural responses, both ipsilaterally and contralaterally.

The standing posture is a fundamental human characteristic for performing several daily tasks, besides contributing significantly to individual independence. Resources from different body systems are required to maintain this posture, especially from the musculoskeletal system. Proprioceptive and force-generating elements, such as the muscle-tendon complex, can perceive stimuli and produce movement (3). The ability to integrate stimuli and promote motor responses is crucial for the proper functioning of the body when controlling posture. Some strategies are adopted for this control in different situations in which the triceps surae musculature, composed of the lateral gastrocnemius, medial gastrocnemius, and soleus, will play an important role (4). The way triceps sural contributes to motor performance and balance is also influenced by its characteristics of counteracting gravity (5) and the mechanical advantage (6) that triceps sural muscles have to produce torque, especially at the ankle joint. It reinforces the importance of this muscle group to several movements that are part of both daily life routines and sports performance.

There are transient conditions that may impair the control of body stability. In this regard, muscle fatigue affects how the triceps surae contributes to postural control due to losses in force production (7). It can also affect the ability of the muscle to receive information from the proprioceptive system causing disturbances in the neuromuscular system, reducing the capacity for muscle force production, increasing body sway, and also the latency of muscle activation in response to body sway (8). Most studies seem to focus on the specific effects of fatigue on postural control evaluating lower limb muscles. As an example, when bilateral ankle muscle fatigue occurs it enhances center of pressure (CoP) oscillation and velocity in the anteroposterior direction, and even when comparing the ankle with hip muscles the triceps surae seems to generate more disturbances on postural control (8). Moreover, when muscle fatigue is inflicted unilaterally on the ankle it is related to less strength contributing to a poor sense of joint position when comparing both limbs (9). Although some studies promoted delayed onset muscle soreness of triceps surae musculature the results were related to how pain affected interlimb communication (10) or it was focused on another musculature, such as knee extensors, and results related to strength and performance evaluated between legs (11). It is noted that studies cited above evaluated the acute postural adaptations following fatigue, or focused parameters besides CoP evaluation when investigating exercise pain. Moreover, it remains unclear how posture control parameters as assessed by CoP responses respond to the presence of exercise-induced delayed onset muscle soreness (DOMS), which is often reported as a late effect following an exercise session leading to fatigue. Triceps surae is important for sports performance considering that its muscle properties, some of those impaired in a DOMS condition, may be related to running economy (12,13). Its relevance is also noted in rehabilitation, especially in the prevention and rehabilitation of Achilles tendon injuries (14,15), in which intense exercises requiring control of the standing posture as well as landing including eccentric muscle actions, are a fundamental part of the treatment routine and required significant participations of the triceps sural (14,16).

Delayed onset muscle soreness (DOMS) is a prevalent condition related to muscle fatigue and can be present in the day-to-day life of both physical therapy and physical training. DOMS is often present after the performance of intense exercise, mainly when the exercise performed is not usual to the individual regarding the range of motion, participation of eccentric muscle actions, abrupt increase in resistance load, and when the individual reaches fatigue (17,18). All these exercise characteristics together lead to muscle damage, which results in a cascade of events resulting in reduced force production and range of motion, increased joint stiffness, and localized edema (17,18). Participants can perceive DOMS a few hours after exercise and will experience the highest magnitudes from 48 to up to 72 hours afterward, with the symptoms most likely disappearing in around 5 to 7 days (18).

Although DOMS recovery seems to follow a natural course of action and most likely will not result in permanent impairments for the participant, a time window of up to 5 to 7 days might significantly impact daily life. In this regard, consecutive days of exercise are not part only of competitive training routines but also rehabilitation processes. While previous researchers look at these relationships considering the sport context, little attention was paid to daily life activities and the general population. Postural control is an important part of the performance of everyday tasks. Furthermore, its importance is noted among elderly people and how impaired postural control affects their daily living activities (19). Thus, understanding how delayed onset muscle soreness influences postural control abilities may have diverse applications, from physical training to rehabilitation.

1.2 RESEARCH PROBLEM

Physical exercise leading to fatigue has the potential to induce muscle damage. First, the acute effect of fatigue is the incapacity of maintaining or generating force through the performance of the exercise (7). The effect of muscle fatigue on postural control is in general described in terms of reduced muscle strength and impairment in proprioceptive feedback (8). Depending on how the fatigue is induced, bilaterally or unilaterally, it will result in less capacity for generating strength. However, the strategy to overcome this impairment will be different because fatigue effects are task-dependent (8).

The damage caused to the muscle fibers and their cytoskeletons as a later effect of fatigue relates to DOMS and increases the regulation of proinflammatory cytokines sensitizing peripheral nociceptors (18). The magnitude of these somatosensory changes may go beyond the periphery and cause central sensitization (20). Among the signs and symptoms is hyperalgesia, which can be primary at the injury site, and secondary when affecting adjacent tissues (21). Moreover, increased stiffness on muscle palpation and decreased joint range of motion can also be observed during DOMS, and minimally affect or completely restrict daily activities from person to person (17). The exercise-induced muscle damage may also reduce neuromuscular performance, impairing the efficiency of the stretching and shortening reflex by decreasing afferent stimuli related to the muscle spindle, Golgi tendon organ, and nerve endings types III and IV (22,23). Moreover, impaired force generation and proprioceptive capacity may generate neuromuscular deficits requiring different motor control strategies (20). As a result, postural control, a primary mechanism necessary to perform activities of daily living, could also be modified. It is important to consider the postural demand when planning the exercise routine post DOMS induction.

The triceps surae can generate large eccentric force at the ankle joint (2), becoming more prone to DOMS (18). This muscle group plays an important role in tasks involving body stability (4) and generating propulsion in gait (2). Furthermore, training and rehabilitation protocols in patients with tendinopathies, those who have undergone Achilles tendon reconstruction, and participants with chronic ankle instability, will routinely include exercises requiring output by a predominance of eccentric muscle actions (10). The eccentric muscle actions will be part of many training and rehabilitation protocols because there are advantages. Four weeks of eccentric training might be enough to promote triceps surae adaptations regarding fascicle length and muscle thickness (24). However, in the context of daily life, the insertion of exercises that potentially can cause muscle damage and DOMS may also influence the performance of daily life tasks. Activities of daily living, such as standing, walking, running, and walking down a step, involve bipedal and unipedal weight-bearing postures in which triceps surae is an agonistic musculature (4,23,25). Since the triceps surae participates in different types of bilateral and unilateral tasks that are part of functional tasks, and this muscle group is also targeted during training and rehabilitation exercise that causes muscle damage, it is relevant to understand whether DOMS bilaterally on triceps surae can affect the performance of static and dynamic postural control tasks.

The assessment of postural control has clinical and non-clinical importance in monitoring body function, risk of falls, and reactive responses, also it is relatively easy to conduct, as it can be done through static postural tasks, such as standing posture under bipedal and unipedal supports (8). In addition, dynamic tasks are also important for assessing postural control. Examples of these tasks are the assessment of the limits of stability, such as the anterior stability limit evaluated during upright standing, and time to stabilization in landing tasks. The limit of anterior stability consists of leaning the body forward aiming to use the amplitude of the ankle joint, an ability important to move between sitting and standing postures or vice versa, as well as to initiate walking and running movements (26). The time to stabilization, which is usually assessed in a drop jump task, will require motor control to manage body acceleration and impact forces to achieve unipedal stance stability (27). In addition, landing on one leg is a challenging task in everyday life, like going up and down steps and running, and used as a form of exercise in rehabilitation and training protocols (28).

We hypothesize that DOMS impairs postural control during unipedal support in both anteroposterior and mediolateral directions. Also, the maximal displacement of anterior stability limit would probably reduce in the presence of DOMS, and a longer time would be needed to stabilize in landing. On the other hand, less challenging tasks, such as bipedal support, would not be impaired by DOMS.

2. RESEARCH GOALS

General goal

To determine whether delayed onset muscle soreness after a maximal exercise on triceps surae muscles affects stability during postural control tasks.

Specific goals

- To quantify the magnitude of delayed onset muscle soreness (DOMS) 48 h after exercise to induce fatigue and damage in the triceps sural.
- To determine the influence of DOMS on the performance of postural tasks involving unipedal quiet standing.
- To determine the influence of DOMS on the performance of postural tasks involving bipedal quiet standing.
- To determine the influence of DOMS on the performance of postural tasks involving active control of body stability.
- To determine the influence of DOMS on the performance of postural tasks involving landing and body stabilization.

3. METHODS

3.1 Participants

This study included 24 participants. Ten were healthy men and 14 were healthy women; their characteristics are detailed in Table 1. The inclusion criteria were to self-report as healthy, with age between 18-35 years, have no history of lower limb injury for at least 6 months, no history of neuromuscular diseases in the last 6 months, no balance and vision disorders, no presence of pain in any part of the body, and no use of medication that interferes with postural control. Exclusion criteria were taking anti-inflammatory and/or any type of pain medication during the study period or not showing up on the second day of the protocol. All participants and researchers had received the vaccine doses for COVID-19 according to the national vaccination schedule. This study was approved by the local ethics committee (CAAE: 26037119.9.0000.5323).

Table 1. Participants characteristics (N=24).

	Mean ± standard deviation
Age (years)	23.80 ± 3.69
Body mass (kg)	68.65 ± 12.67
Height (m)	1.69 ± 0.08
Body mass index - BMI (kg/m²)	24.73 ± 3.90
Physical activity (minutes per week)	227.40 ± 135.60

The GPower software (GPower 3.1.9.7, Franz Faul, Universität Kiel, Germany) was used to calculate the expected sample size. Sample size estimation was conducted considering the paired t-test statistical model, with an effect size of 0.6, a statistical power of 80%, and an alpha of 0.05. The sample size calculation indicated the inclusion of 24 participants. To anticipate potential losses, three additional participants were recruited. In total 27 people were recruited and 3 were excluded from the sample due to not attending one of the evaluation sessions. The experimental design involved two visits to the laboratory with 48 h of interval between them. The first day consisted of participants answering a questionary for the identification and collection of personal data, and providing individual signature on the informed consent form. Afterward, the level of muscle soreness was evaluated through the numeric rate scale and also the pressure pain threshold, followed by the performance of the stability tests, in a random order, and finally the exercise for induction of DOMS was performed. 48 h later, participants returned to the laboratory to repeat soreness and postural control assessments.

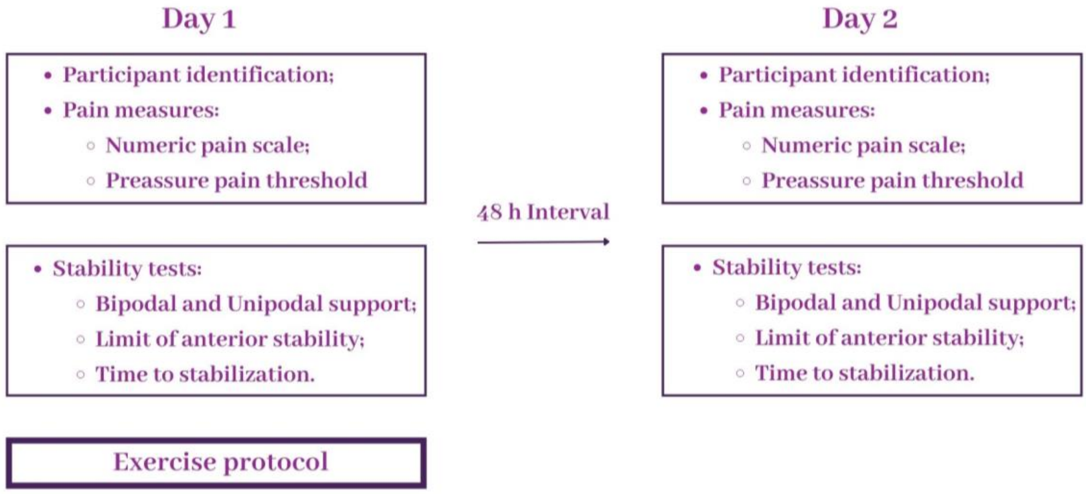

Figure 1. Experimental design.

The information for identification of the participants related to name, age, sex, and hours of physical activity per week was collected through a questionnaire customized by the researchers. The measurements of body mass and height were obtained using an analog industrial scale. Body mass index (BMI) was calculated using the standard equation (BMI = body mass / height^2).

3.2 Stability tests

All the stability tests were standardized before the main experiment through a pilot study and adaptations were performed if necessary. To avoid possible influences on the results, the order of the tests was randomly arranged for each participant. Furthermore, all stability tests were performed in a private room, with the presence of each participant and two researchers. Stability was assessed pre and 48 h post-inducing delayed onset muscle soreness. A kinetic assessment was performed using a force platform (OR6-2000, AMTI Inc., Maryland, USA) embedded at the floor level in the center of a quiet room to obtain the values of the three-dimensional ground reaction forces and moments (29). Force signals were sampled at 100 Hz for bipedal, unipedal support, and limit of anterior stability (30), while in the time to stabilization task signals were registered at a sampling rate of 1000 Hz (27). All participants completed 3 trials of familiarization before each stability task and received the same instructions.

3.2.1 Upright quiet standing

For assessment of upright standing, participants stood upright with their arms resting along the body, feet placed apart at the same distance from their shoulders at a comfortable position being instructed to look at a symbol positioned about 3 m ahead at their eyes level. Three trials lasting 30 s each (31) were performed with bipedal support, and three trials of similar duration were performed with unipedal support. The leg preference for unipedal stance support was determined as the contralateral leg preferred to kick a ball (32). The calculation of the displacement of the center of pressure (CoP) in the anteroposterior and mediolateral directions was performed as proposed by Winter (29). The CoP variables were the anteroposterior and mediolateral amplitude of displacement of the center of pressure (CoPmax-CoPmin), the area of the ellipse including 95% of CoP data, and the resultant velocity (Figure 2a and 2b).

3.2.2 Limit of anterior stability

The limit of anterior stability (LoS) was assessed while the participants were standing upright, with the arms crossed over the chest and feet placed apart at the same distance from their shoulders at a comfortable position (33). For the assessment, the participants should lean the body forward relying on the ankle sagittal plane range of motion, keeping trunk and legs aligned, aiming to reach the maximal anterior displacement and return to the initial position without losing balance. Each trial was divided into 2 phases. In phase 1, the participants should remain standing still for 5 s, and only after a verbal signal from the evaluator lean the body forward. The movement should be done relying on the ankle joint without flexing the trunk to reach the maximal forward displacement and sustain the posture for 7 s. In the subsequent phase 2, the evaluator gave the signal to the participants, that they should return to the initial position of upright standing for up to 5 s (Figure 2c).

The following variables were determined in phases 1 and 2: CoP amplitude, area of the ellipse including 95% of CoP data, and CoP velocity in the anteroposterior direction. To identify in which phase there was more variability for CoP data, the ratio between the CoP displacements in phase 2 and phase 1 was calculated considering the measures in the anteroposterior and mediolateral direction pre and post 48 h exercise. A ratio higher than one indicates larger CoP displacement during phase 2 compared to phase 1. The velocity to reach phase 2 was calculated in each trial pre and 48 h post exercise. A custom-made code was written to calculate CoP data in each phase (MATLAB 2015a, The MathWorks Inc. Natick, Massachusetts, USA).

3.2.3 Time to stabilization

The time to stabilization (TTS) task involved the performance of a single-leg landing and followed the protocol developed in a previous study (27). In this protocol, trials were performed with the same leg preferred for the unipedal stance. A box with 20 cm height, was placed 10 cm before the force plate was used. Participants were instructed to stand at the top of the box, keep their hands on their hips and step out of the box "*as if falling from a step*", landing and maintaining a stable posture for up to 7 s (Figure 2d). Three familiarization trials were performed, and three valid trials were recorded. To be a valid trial, the participant should not move the foot after landing, do not use the contralateral foot for support, and do not change hands position. The time to stabilization was obtained from the unfiltered vertical component of the ground force reaction data through a custom-made code (MATLAB 2015a, The MathWorks Inc. Natick, Massachusetts, USA). The initial contact with the ground was defined by 10 N raise in the vertical component of the ground force reaction, and stability was considered when the vertical component of the ground reaction force oscillation was within a range of 5% of body weight, having an upper limit greater than 2.5% (102.5%) and less than 2.5% (97.5%) of body weight (100%). The distance from first to the final intersection of the upper and/or lower limit was defined as the stability time. Trials in which the stabilization lasted more than 6 s were considered by the responsible for the analysis as *“not reached stability*” and excluded from further analysis.

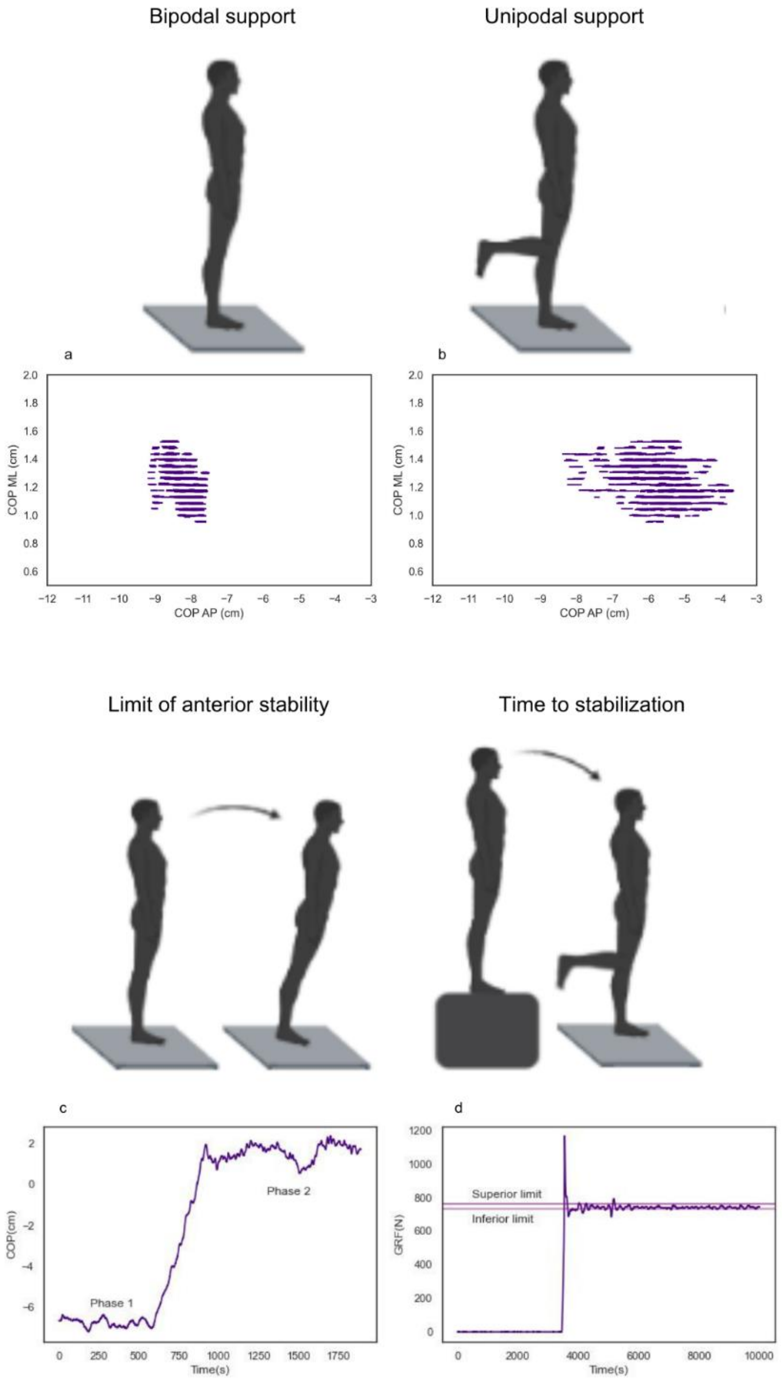

Figure 2. Illustration of the postural tasks and representative data from one subject corresponding to (a) mediolateral and anteroposterior displacement of center of pressure during bipedal support, (b) unipedal support (scale x=-12: -3 and y=0.5:2), (c) anterior displacement of center of pressure during the limit of anterior stability, and (d) vertical component of ground reaction force during the time to stabilization task with superior and inferior limits regarding 5% of body weight.

3.3 Exercise protocol to induce DOMS

The participants performed an exercise protocol to induce DOMS. This protocol involved the heel rise exercise to recruit calf muscles with a significant amount of eccentric actions in the triceps surae musculature, and therefore with great potential to generate muscle damage and DOMS (34). The exercise was performed using a step on which the participants were standing upright in front of a wall and supporting the body weight only with the anterior part of the foot allowing the rest of the joint to perform the full amplitude of movement for the plantar flexion (concentric phase) and dorsiflexion movement (eccentric phase). They were allowed to touch the wall to help stabilize the posture while performing the heel rise movement with a full range of motion. In the first set, the participants should perform the maximal number of repetitions possible until voluntary fatigue, thus establishing a 100% reference. On the second set, they should perform at least 75% of the number of repetitions from the first set. Subsequent sets were repeated until the participants could not achieve several repetitions corresponding to 50% of the maximum repetitions of the first set. The cadence was controlled by a metronome (40 Hz), considering a set of plantar flexion and dorsiflexion as 1 repetition. An interval equal to the time performed during the exercise was allowed between the sets.

3.4 DOMS assessment

The presence of DOMS was evaluated through a numeric rate scale (NRS) ranging from 0 (no pain) to 10 (worst pain ever felt) and the pressure pain threshold (PPT) using a digital algometer with a resolution of 0.05 N/cm² and a smooth circular tip (Instrutherm - Portable digital dynamometer - model DD-500). For the NRS assessment, the participants were seated on a stretcher with their feet hanging without contact with any surface. For PPT assessment participants were positioned in ventral decubitus on a stretcher. The PPT was determined through one measurement for each leg by a researcher with experience in using the algometer. The location to apply the pressure was made through a measurement determining the point corresponding to half of the leg from heel to popliteal fossa using a measuring tape to maintain the standardization through the participants. The algometer was positioned perpendicular to the skin at the mentioned location, then pressed slowly and gradually (35). The instruction given to each participant consisted of reporting to the evaluator when the pressure made by the algometer became painful. The determined site was marked with a pen to ensure that it was assessed 48 h later.

Both measures were performed on the first day, before the postural performance of postural tasks and the exercise protocol to induce DOMS, and 48 h later, before the postural performance of postural tasks.

3.5 Statistical analysis

Statistical analyses were performed using a commercial package (IBM SPSS statistical package, Version 26) and a significance level set at 5%. Plots of data were made using Python 3 in Jupyter notebook. The normality of data distribution was checked with the Shapiro-Wilk test and according to the outcomes, the data were treated as parametric or non-parametric.

Numeric scale data (n=24) were compared pre and 48 h post DOMS induction by one-sample t-test against the theoretical mean equal 0 (zero) since 22 participants answered 0 (no pain) on the first day and 3 answered 1. PPT was compared considering the average of both legs pre and 48 h post DOMS induction by paired t-test (n=22).

CoP outcomes for upright on bipedal and unipedal support tasks were compared pre and 48 h post DOMS induction using paired t-tests (unipedal anteroposterior and mediolateral CoP amplitude) and Wilcoxon tests (CoP resultant velocity, area of the ellipse including 95% of CoP data from bipedal and unipedal support).

Limits of stability data corresponding to anteroposterior and mediolateral displacement, velocity, and area of the ellipse including 95% of CoP data were evaluated for phases 1 and 2 separately. Most variables were compared pre and 48 h post DOMS induction using paired t-tests (n=19), but mediolateral CoP amplitude and area of the ellipse including 95% of CoP data were compared using Wilcoxon tests. The anterior and mediolateral maximum displacement and proportion of oscillation were compared between pre and 48 h post exercise using paired t-test and Wilcoxon test, respectively. The velocity to reach phase 2 was compared between pre and 48 h post exercise using a paired t-test.

The time to stabilization test (n=18) was first submitted to a frequency analysis to determine the number of participants able to reach stability. Data considering those able to stabilize were compared pre and 48 h post DOMS induction using paired t-test.

The effect size for all the statistically significant differences was determined using Glass delta (e.g., $GD = (\frac{meanPost - meanPre}{STDpre})$ for parametric data, considering GD< 0.1: null, 0.2 < GD > 0.1: very small, 0.5 < GD >0.2: small, 0.8 < GD > 0.5: medium, 0.5 < GD > 1.2: large; GD > 1.2: very large (36,37). For non-parametric data, the probability of superiority (e.g., $PS = \left(\frac{n+}{\Sigma(n+ and\ n-)}\right)$ in which n+ are positive differences and n- are negative differences), was considered as the probability of a randomly selected score from 48 h post exercise to be superior over a randomly selected score from the pre exercise (37).

4. RESULTS

The exercise protocol induced DOMS. DOMS resulted in higher numeric rate scale (NRS) points 48 h post exercise compared to pre-exercise (6.04 ± 2.40 points; $p = 0.001$). The pressure pain threshold (PPT, Figure 3) reduced in DOMS condition (pre: 38.28 ± 15.48 and 48 h post exercise: 30.69 ± 14.47 N/cm²; $p = 0.001$, GD = 0.49, small).

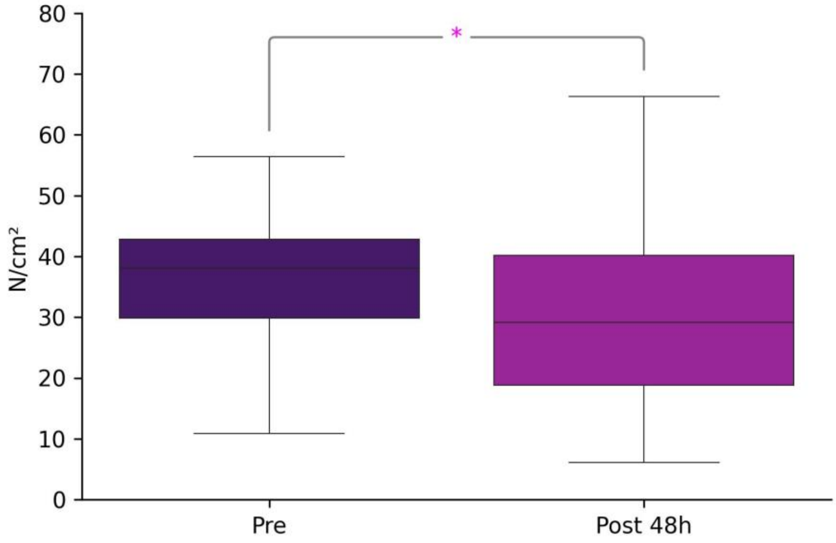

Figure 3. Pressure pain threshold results pre and post 48h (n=22). * Indicates pre vs. post 48 h difference.

Center of pressure (CoP) data during bipedal support did not differ between pre and 48 h post exercise when DOMS was present. The CoP amplitude in anteroposterior (median pre 1.90 and post 2.15 cm; $Z = -0.745$; $p = 0.456$) and mediolateral directions (median pre 1.35 and post 1.54 cm; $Z = -1.794$; $p = 0.073$), as well as the area of the ellipse including 95% of CoP data (median pre 1.68 and post 2.72 cm^2; $Z = -1.257$; $p = 0.209$) and resultant velocity (median pre 2.34 and post 2.49 cm/s; $Z = -1.347$; $p = 0.178$) did not differ between pre and post 48 h.

Unipedal support showed a higher amplitude of CoP in the mediolateral direction in the presence of DOMS 48 h post exercise (pre 2.52 ± 0.31 and post 3.26 ± 0.50 cm, $p<0.001$; GD = 2.39, very large; Figure 4). No differences were found between pre and 48 h post exercise for CoP amplitude in the anteroposterior direction (pre 4.60 ± 1.08 and post 4.82 ± 1.25 cm; $p = 0.296$), area of the ellipse including 95% of CoP data (median pre 9.25 and post 10.36 cm^2; Z = -1.38; $p= 0.168$), and resultant velocity (median pre 5.24 and post 5.20 cm/s; Z = -0.4; $p = 0.689$).

Table 2. Center of pressure behavior during bipodal and unipedal tasks. Data expressed as median (minimum – maximum) values.

	Pre	Post 48 h	p-value
Bipodal			
AP displacement (cm)	1.90 (1.13 – 4.74)	2.15 (1.18 – 4.12)	0.456
ML displacement (cm)	1.35 (0.60 – 5.11)	1.54 (0.82 – 3.96)	0.073
Velocity (cm/s)	2.34 (1.57 - 3.28)	2.49 (1.64 – 4.33)	0.178
Area (cm^2)	1.68 (0.47 – 6.59)	2.72 (0.60 – 8.45)	0.209
Unipedal			
AP displacement (cm)	4.33 (3.18 – 7.72)	4.73 (1.36 – 7.14)	0.296
ML displacement (cm)	2.48 (1.96 - 3.0)	3.16 (2.61 - 4.48)	<0.001*
Velocity (cm/s)	5.24 (3.87 – 7.75)	5.20 (4.26 – 7.48)	0.689
Area (cm^2)	9.25 (6.49 – 15.50)	10.36 (6.59-21.75)	0.168

AP: anteroposterior; ML: mediolateral; CoP task: center of pressure corresponding to the specific task.

* Indicates pre vs. post 48 h difference.

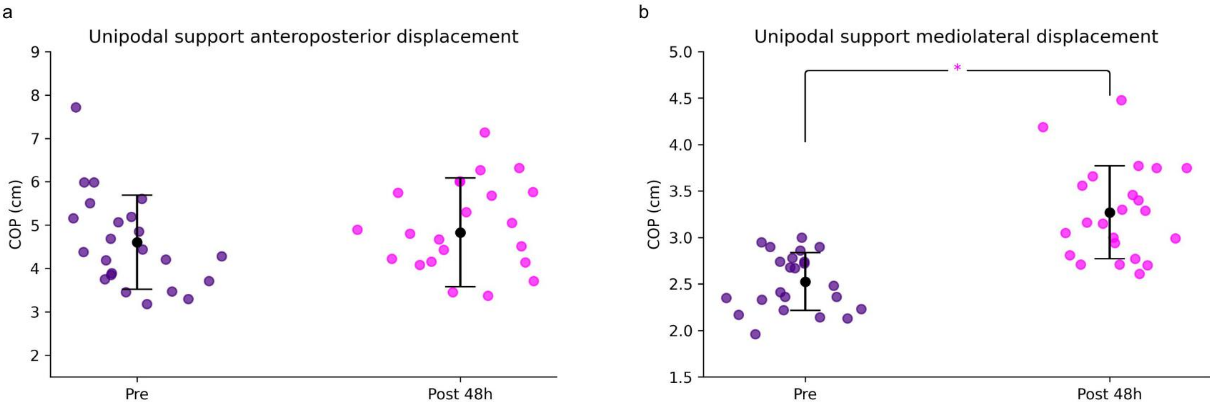

Figure 4. Anteroposterior and mediolateral displacement of the center of pressure during unipedal support. Pre and post 48h of exercise. * Indicates pre vs. post 48 h difference (n = 24).

In phase 1 of the limit of anterior stability task, which involved the upright quiet posture, we found a higher amplitude of CoP in the mediolateral direction 48 h post exercise when DOMS was present (pre 0.79 ± 0.30 and post 0.97 ± 0.40 cm, p = 0.031; GD = 0.57, medium; Figure 5a) and velocity (pre 1.23 ± 0.19; post 1.36 ± 0.29 cm/s; p= 0.037; GD = 0.68, medium; Figure 5b). No statistical difference was found regarding anteroposterior displacement (pre 1.68 ± 0.50 post 1.72 ± 0.48 cm p = 0.755), velocity (pre 1.93 ± 0.35 post 1.98 ± 0.37 cm/s; p = 0.397) and area (median 1.03 pre and post 1.52 cm^2; Z = -1.811 ; p = 0.07).

When analyzing data from phase 2, in which the anterior displacement was performed, the amplitude of CoP in the mediolateral direction was higher 48 h post exercise compared to pre-exercise (median pre 1.19 and post 1.50 cm; Z = - 2.504; p=0.012; PS = 47.4%; Figure 5c). No differences were found regarding anteroposterior displacement (median pre 2.56 and post 2.12 cm; Z = -0.684; p=0.494), velocity (pre 2.30 ± 0.43 post 2.37 ± 0.51 cm/s; p = 0.416) and area (median pre 2.48 and post 3.19 cm^2; Z = -1,730 ; p = 0.08). In addition, the proportion of displacement was higher (>1) for both anteroposterior (pre 1.41 ± 0.24 and post 1.50 ± 0.28 a.u., p =0.019; GD = 0.36, small) and mediolateral directions 48 h post exercise in presence of DOMS (median pre 1.50 and post 0.65 a.u.; Z = -2.678; p = 0.007, PS = 16,7%). No differences were found comparing CoP velocity to reach phase 2 pre and post 48 h (pre 5.17 ± 2.09 and post 5.06 ± 1.87 cm/s, p = 0.769). The information cited above can be seen in Table 3.

There were 5 participants unable to reach stability in the TTS task, and for one additional participant, we had problems with signal processing. We made an exploratory analysis for the time to stabilization task and found that 10 participants needed a longer time to stabilize, while 8 participants needed a shorter time to stabilize when comparing the performance pre and post 48 h (Figure 6). Overall, pre and post 48 h showed no difference in time to stabilization (pre 2.68 ± 1.57 and 2.86 ± 1.66 s, p = 0.683). Also, a high coefficient of variation and standard deviation was found overall during the performance of the time to stabilization task (CV pre 58.6 ± 1.58 and post 57.8 ± 1.66%).

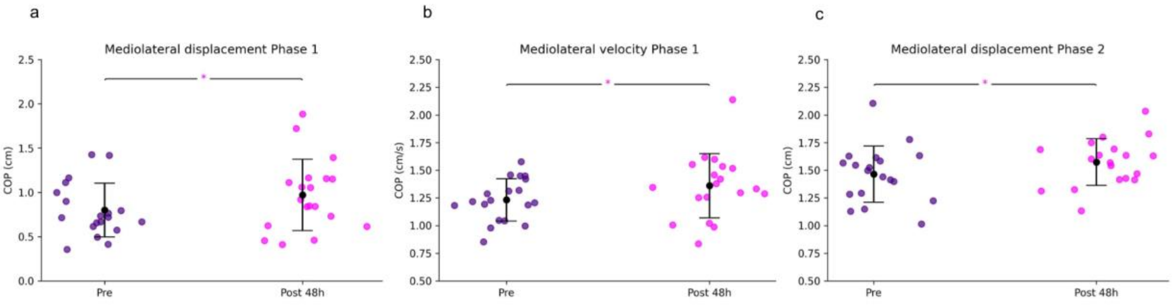

Figure 5. Mediolateral displacement and velocity from the limit of anterior stability. a) mediolateral displacement in phase 1; b) mediolateral velocity in phase 1; c) mediolateral displacement in phase 2. All measures pre and post 48 h post exercise. * Indicates pre vs. post 48 h difference (n = 19).

Table 3. Center of pressure behavior during limit of stability task on phase 1, phase 2, maximum inclination, the proportion of oscillation, velocity of body inclination.

LEA	Pre	Post 48h	p-value
Phase 1			
AP displacement (cm)	1.68 ± 0.50	1.72 ± 0.48	0.755
ML displacement (cm)	0.79 ± 0.30	0.97 ± 0.40	0.031*
AP Velocity (cm/s)	1.93 ± 0.35	1.98 ± 0.37	0.397
ML Velocity (cm/s)	1.23 ± 0.19	1.36 ± 0.29	0.037*
Area (cm^2)	1.29 ± 0.84	1.67 ± 0.93	0.070
Phase 2			
AP displacement (cm)	2.39 ± 0.59	2.49 ± 0.86	0.494
ML displacement (cm)	1.14 ± 0.36	1.37 ± 0.38	0.012*
AP Velocity (cm/s)	2.30 ± 0.43	2.37 ± 0.51	0.416
ML Velocity (cm/s)	1.46 ± 0.25	1.57 ± 0.21	0.107
Area (cm^2)	2.78 ± 1.44	3.45 ± 1.75	0.084
Maximum inclination			
AP displacement (cm)	10.26 ± 2.16	9.89 ± 1.56	0.366
ML displacement (cm)	0.65 ± 0.35	0.66 ± 0.44	0.841
Proportion of oscillation			
AP (phase2/phase1)	1.41 ± 0.24	1.50 ± 0.28	0.019*
ML (phase2/phase1)	1.35 ± 0.53	0.65 ± 0.45	0.007*
Velocity of body inclination (cm/s)	5.17 ± 2.09	5.06 ± 1.87	0.769

Mean ± standard deviation; * indicates pre vs. post 48 h difference.

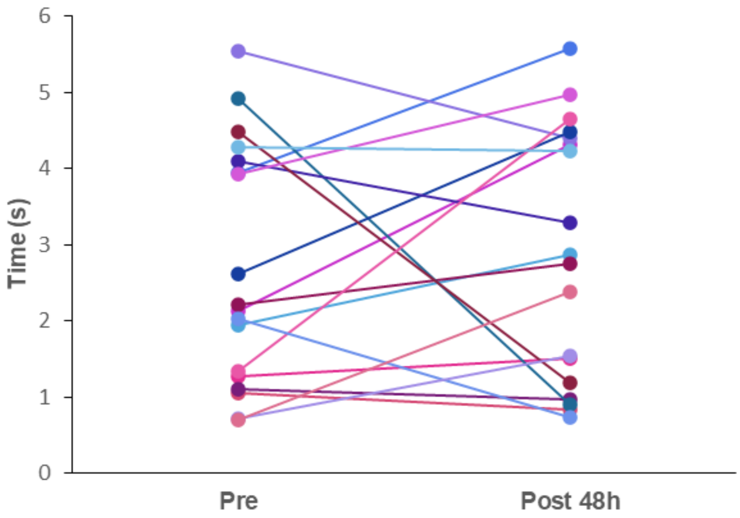

Figure 6. Exploratory analysis from individual results in time to stabilization task pre and post 48h of DOMS induction (n=18).

5. DISCUSSION

The primary goal of this study was to determine whether delayed onset muscle soreness (DOMS) after a maximal exercise causing fatigue in the triceps surae muscle group affects stability during the performance of unipedal and bipedal postural control tasks. In summary, we found that the mediolateral component of the center of pressure (CoP) during postural task is are more sensitive to DOMS in the triceps sural muscles. The changes observed suggest that the mediolateral control of the center of pressure is impaired when DOMS is present. There are different practical implications of these results. The first consists of the influence of a lack of mediolateral control of center of pressure on control of upright posture and its associations with an increased risk of fall (38,39). Interestingly, although the anteroposterior body oscillation seems to rely more on sagittal movements of the ankle joint, in which triceps sural is more recruited (6), we have not found differences in center of pressure anteroposterior outcomes when comparing pre and post 48 h results.

Considering the often inclusion of exercises recruiting the triceps sural in both training and rehabilitation programs (26,40), the presence of DOMS can be assumed as a risk for impaired stability in consecutive days of exercise. In many cases, as for the case of prevention programs for Achilles tendon injuries, triceps sural is submitted to exercises involving higher eccentric loads and the need for proper body stability (24,41). Based on our results, it seems that when such exercises lead to DOMS, attention should be paid to the configuration of the consecutive sessions of exercise due to the effects observed for mediolateral displacement of the center of pressure. In addition, heel rise exercise is also important to promote strength gains in older adults (42). For this population, our results may have an additional implication regarding the risk of falls, as impaired mediolateral control of the center of pressure is an additional factor for the risk of falls (43). Although we have limited our experimental tests to the control of upright standing postures, it would be expected that such an effect may impair also the control of dynamic tasks, such as weight-bearing exercises and hop tests commonly employed in physical training and rehabilitation. These hypothetical effects, however, still claim for further research.

We initially induced and quantified the magnitude of DOMS in our participants. It would be important to have an exercise protocol that would ensure the presence of DOMS. We found participants reporting higher score of pain according to the numeric rate scale and a lower pressure pain threshold post 48 h of exercise, indicating the presence of soreness and more sensitivity to pain. We already expected these changes to happen as found in previous studies (34,44). Despite the small effect size observed for PPT (GD = 0.49), these results support the presence of DOMS in our participants. Furthermore, although the two methods used for the measurement of muscle soreness showed similar outcomes, we consider it important to use more them one method when analyzing pain since unidimensional scales sometimes can be less sensitive to changes (45) and also because mechanical hyperalgesia can be a major consequence of DOMS (20).

Our rationale for including different postural tasks was to expose participants to tasks eliciting different levels of difficulty, under the assumption that any effect would also rely on the task difficulty. We found some results that support this assumption. The center of pressure during the bipodal support postural task was not affected by the presence of DOMS. Under bipodal support, the participants have a low level of challenge for the postural task. In previous studies, authors opted to test this task while eyes were closed (16,46,47), but in our case, we decided to test only open eyes condition to minimize confounding factors. Therefore, the lack of difference between pre and post 48 h condition may rely on the fact that triceps surae is not the only musculature responsible for standing stability, and bipodal standing requires low magnitudes of triceps sural muscle activity and force production (6). Considering postural control as dependent on sensorial inputs from mechanoreceptors detecting changes in length and tension of the muscle, the type of exercise performed and the small magnitudes of articular movement needed during bipodal standing may result in low muscle recruitment being necessary to counteract changes in muscle length (48).

Postural tasks can have difficult to manipulate by altering the configuration of the support base. A reduced base of support is expected to make postural control more difficult (6). The unipedal task showed higher oscillation only on mediolateral displacement and it appears to be the most consistent measure considering the effect size (GD = 2.39). Thus, this direction is the most affected in elderly people during postural tasks and gait (39,49). Moreover, during a demanding task, such as unipedal support, the anteroposterior CoP control could rely on other muscles that are also responsible for stabilizing posture, such as the hip (46,50). Contrary to the anteroposterior control, the mediolateral CoP component requires stabilization of more degrees of freedom, inducing the system to work in a synergic and more demanding way (51) even during bipedal standing (6). Although we do not evaluate the muscle activity from lower limbs, it is important to consider that the triceps surae is just a part of the muscle synergy that occurs when controlling posture (6,50).

When addressing the role of the triceps surae for postural control, literature overwhelming supports the concept that the stretching of this muscle group results in significant stimuli for mechanoreceptors in both muscle and tendon that provide the central nervous system with sensorial information for movement regulation (41). Therefore, we consider that including the assessment of a motor task causing muscle stretching would enable us to discuss the impact of DOMS on the ability of the central nervous system to receive and use this information. In the task named limit of anterior stability, the participant should keep the upright standing and then lean the body forward relying mostly on the ankle control to sustain the posture, and then return body posture to the start position (30). Triceps surae was therefore first stretched while producing force, acting in an eccentric form, and then required to contract under concentric actions to return the position.

We found higher mediolateral center of pressure velocity and displacement while the lean movement was performed when DOMS was present compared to the pre-evaluation. Considering that the anteroposterior center of pressure displacement did not differ between pre and post DOMS induction, we hypothesize that participants may have increased mediolateral body oscillations during the performance of the task. The reason for this behavior may rely on asymmetrical patterns of the center of pressure under DOMS conditions, similar to what is observed in other participants during fatigue (8,32). While we have not quantified the center of pressure over each of the feet, the increased mediolateral displacement of the center of pressure is generally assumed as an indicator of poor stabilization capacity (43). We found that participants are able to perform the task while reporting significant DOMS, but the higher mediolateral displacement may suggest the recruitment of additional muscle to produce the necessary magnitude of force for the control of body posture (6). Future studies employing techniques to monitor neuromuscular electrical activity may provide additional insights in this regard, as well as the test of different DOMS conditions, like a unilateral DOMS as a plausible intervention to investigate the associations of DOMS with larger mediolateral instabilities.

We have also considered a task involving impact absorption and stability control as part of our experiment. In this task, we combined the DOMS with a context in which participants would have to deal with body movement causing additional acceleration and then quickly establish a stable posture. Different from our initial hypothesis, the time to stabilization did not differ between the condition pre and post 48 h when DOMS was present. Our rationale for this task was that DOMS and its symptoms would limit the ability to control body position. We argue that the lack of a DOMS effect is likely resultant of the muscle group in which DOMS was induced. In the landing task considered, there is a strong participation of the quadriceps muscles to control knee position rather than recruitment of the triceps sural (52). When going through an exploratory analysis we observed mixed responses between the participants, indicating different strategies to deal with the task. This could be related to the degrees of freedom problem, showing that more than one way can be used to resolve the same motor task (50). Also, muscle fatigue and its effects are task-dependent (7), and this activity of stepping was not similar to the activity that induced fatigue and soreness through exercise. On the other hand, it could also be related to the method to calculate the time to stabilization and the variability related to the nature of the task (53). Another study with similar participants characteristics, but considering the pre-exercise context, did not find corresponding times (27). Another way to look into this data would be by analyzing the center of pressure during the landing (39).

Regarding limitations to the study, we had different levels of training among the participants when comparing each person. Also, we found some variability related to the anterior limit of the stability task and time to stabilization. In addition, the postural effects could have a different time course than DOMS, and for future studies, it should be evaluated also before the 48 h. Here we did not consider differences between sexes, but DOMS can affect differently each sex (44) and should be considered for future studies.

For future studies, we suggest considering a wider range of possible sample losses and also the variability among participants when computing the sample size. Moreover, perception of effort and isometric force could be used to control the level of fatigue. Also, an electromyographic analysis could help to understand the pattern of activation during different types of postural control tasks after a perturbation.

6. CONCLUSION

Under the condition of exercise-induced delayed onset muscle soreness in the triceps surae, the participants experience difficulties in controlling the mediolateral component of their center of pressure, especially during unipedal standing and active body stabilization when moving forward. It appears that managing this aspect becomes particularly challenging when experiencing exercise-related pain.

These findings highlight the importance of assessing and conducting tasks in the sagittal plane during both training and treatment sessions. Additionally, our study revealed diverse outcomes, suggesting that different strategies should be employed based on the task's level of difficulty. The variability among participants emphasizes the necessity to evaluate each individual separately when designing an exercise or rehabilitation program.

7.REFERENCES

1. Shumway-Cook A, Woollacott MH. Controle Motor: Teorias e aplicações práticas. 2nd ed. Editora Manole Ltda.; 2003. 591 p.
2. Hamill J, Knutzen KM, Derrick TR. Bases biomecânicas do movimento humano. 4th ed. São Paulo: Editora Manole Ltda.; 2016. 501 p.
3. Macefield VG, Knellwolf TP. Functional properties of human muscle spindles. J Neurophysiol [Internet]. 2018 [cited 2023 Mar 22];120:452–67. Available from: www.jn.org
4. Honeine J-L, Schieppati M, Gagey O, Do M-C. The Functional Role of the Triceps Surae Muscle during Human Locomotion. Kreplak L, editor. PLoS One [Internet]. 2013 Jan 16 [cited 2021 Oct 4];8(1):e52943. Available from: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0052943
5. Honeine J, Schieppati M, Gagey O, Do M. By counteracting gravity, triceps surae sets both kinematics and kinetics of gait. Physiol Rep [Internet]. 2014 Feb [cited 2021 Oct 4];2(2):e00229. Available from: /pmc/articles/PMC3966244/
6. Macefield VG, Knellwolf TP. Functional properties of human muscle spindles. J Neurophysiol [Internet]. 2018 Aug 1 [cited 2021 Nov 24];120(2):452–67. Available from: https://doi.org/10.1016/B978-0-444-63916-5.00004-5
7. Enoka RM, Duchateau J. Muscle fatigue: what, why and how it influences muscle function. J Physiol [Internet]. 2008 Jan 1;586(1):11–23. Available from: http://doi.wiley.com/10.1113/jphysiol.2007.139477
8. Penedo T, Barbieri FA. EFEITO DA FADIGA MUSCULAR NA SIMETRIA DO CONTROLE POSTURAL EM ADULTOS JOVENS [Internet]. Bauru: Universidade Estadual Paulista (UNESP); 2018 Apr [cited 2021 Jun 3].

Available from: https://repositorio.unesp.br/handle/11449/153886

9. Vuillerme N, Boisgontier M. Muscle fatigue degrades force sense at the ankle joint. Gait Posture [Internet]. 2008 Oct 21 [cited 2022 Oct 27];28(3):521–4. Available from: https://hal.archives-ouvertes.fr/hal-00283883
10. Gervasio S, Finocchietti S, Stevenson AJT, Mrachacz-Kersting N. Delayed muscle onset soreness in the gastrocnemius muscle attenuates the spinal contribution to interlimb communication. Eur J Appl Physiol [Internet]. 2018 Nov 21 [cited 2021 Oct 5];118(11):2393–402. Available from: https://pubmed.ncbi.nlm.nih.gov/30132112/
11. Hedayatpour N, Izanloo Z, Falla D. The effect of eccentric exercise and delayed onset muscle soreness on the homologous muscle of the contralateral limb. J Electromyogr Kinesiol [Internet]. 2018 Aug;41:154–9. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1050641118300166
12. Bohm S, Mersmann F, Santuz A, Arampatzis A. Enthalpy efficiency of the soleus muscle contributes to improvements in running economy. Proc R Soc B Biol Sci [Internet]. 2021 Jan 27;288(1943):20202784. Available from: https://royalsocietypublishing.org/doi/10.1098/rspb.2020.2784
13. Albracht K, Arampatzis A. Exercise-induced changes in triceps surae tendon stiffness and muscle strength affect running economy in humans. Eur J Appl Physiol [Internet]. 2013 Jun 18;113(6):1605–15. Available from: http://link.springer.com/10.1007/s00421-012-2585-4
14. Brorsson A, Willy RW, Tranberg R, Grävare Silbernagel K. Heel-Rise Height Deficit 1 Year After Achilles Tendon Rupture Relates to Changes in Ankle Biomechanics 6 Years After Injury. Am J Sports Med [Internet]. 2017 Nov 7 [cited 2022 Dec 1];45(13):3060–8. Available from:

http://journals.sagepub.com/doi/10.1177/0363546517717698

15. Fernandes GL, Orssatto LBR, Shield AJ, Trajano GS. Runners with mid-portion Achilles tendinopathy have greater triceps surae intracortical inhibition than healthy controls. Scand J Med Sci Sports [Internet]. 2022 Apr 18;32(4):728–36. Available from: https://onlinelibrary.wiley.com/doi/10.1111/sms.14111
16. Hall EA, Chomistek AK, Kingma JJ, Docherty CL. Balance- and Strength-Training Protocols to Improve Chronic Ankle Instability Deficits, Part I: Assessing Clinical Outcome Measures. J Athl Train [Internet]. 2018 Jun 1;53(6):568–77. Available from: https://meridian.allenpress.com/jat/article/53/6/568/112282/Balance-and-StrengthTraining-Protocols-to-Improve
17. Cheung K, Hume PA, Maxwell L. Delayed Onset Muscle Soreness. Sport Med [Internet]. 2003 [cited 2021 Jun 3];33(2):145–64. Available from: http://link.springer.com/10.2165/00007256-200333020-00005
18. Hotfiel T, Freiwald J, Hoppe M, Lutter C, Forst R, Grim C, et al. Advances in Delayed-Onset Muscle Soreness (DOMS): Part I: Pathogenesis and Diagnostics. Sport · Sport [Internet]. 2018 Dec 11 [cited 2021 Sep 9];32(04):243–50. Available from: https://pubmed.ncbi.nlm.nih.gov/30537791/
19. Thomas E, Battaglia G, Patti A, Brusa J, Leonardi V, Palma A, et al. Physical activity programs for balance and fall prevention in elderly. Medicine (Baltimore) [Internet]. 2019 Jul;98(27):e16218. Available from: https://journals.lww.com/00005792-201907050-00047
20. Courtney CA, Aoyagi K, Fernández-de-las-Peñas C, Madeleine P. BILATERAL SENSORY DEFICITS AND WIDESPREAD HYPERALGESIA OCCUR FOLLOWING INDUCED DELAYED ONSET MUSCLE SORENESS OF THE

QUADRICEPS. Int J Sports Phys Ther [Internet]. 2020 Feb [cited 2021 May 23];15(1):12–21. Available from: /pmc/articles/PMC7015021/

21. Urban MO, Gebhart GF. Supraspinal contributions to hyperalgesia. Proc Natl Acad Sci [Internet]. 1999 Jul 6 [cited 2021 Oct 1];96(14):7687–92. Available from: /pmc/articles/PMC33602/

22. Komi P V. Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. J Biomech [Internet]. 2000 Oct 1 [cited 2021 Oct 1];33(10):1197–206. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0021929000000646

23. Ledin T, Fransson PA, Magnusson M. Effects of postural disturbances with fatigued triceps surae muscles or with 20% additional body weight. Gait Posture [Internet]. 2004 Apr;19(2):184–93. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0966636203000614

24. Geremia JM, Baroni BM, Bini RR, Lanferdini FJ, de Lima AR, Herzog W, et al. Corrigendum: Triceps Surae Muscle Architecture Adaptations to Eccentric Training. Front Physiol [Internet]. 2020 Jul 3;11. Available from: https://www.frontiersin.org/article/10.3389/fphys.2020.00627/full

25. Lehnen GCS, Rodrigues FB, Galvão JMA, Andrade AO, Vieira MF. Effects of triceps surae fatigue and weight training level on gait variability and local stability in young adults. Med Biol Eng Comput [Internet]. 2020 Aug 5;58(8):1791–802. Available from: https://link.springer.com/10.1007/s11517-020-02196-8

26. Molina-Rueda F, Cuesta-Gómez A, Carratalá-Tejada M, Koutsou A, Fernández-González P, Alguacil-Diego IM. Ankle muscle activation during the limits of stability test in subjects with chronic ankle instability. Phys Ther Sport

[Internet]. 2021 Jan 1 [cited 2023 Mar 22];47:134–9. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1466853X20305939

27. Byrne A, Lodge C, Wallace J. Test–Retest Reliability of Single-Leg Time to Stabilization Following a Drop-Landing Task in Healthy Individuals. J Sport Rehabil [Internet]. 2021 Nov 1 [cited 2022 Jul 11];30(8):1242–5. Available from: https://journals.humankinetics.com/view/journals/jsr/30/8/article-p1242.xml

28. Mao M, Yin Y, Luo D, Liu H, Yu B. Evaluation of dynamic postural control during single-leg landing tasks using initial impact force, landing leg stiffness and time to stabilisation. Sport Biomech [Internet]. 2021 Feb 17 [cited 2023 Feb 28];1–14. Available from: https://pubmed.ncbi.nlm.nih.gov/33594918/

29. Winter DA, Prince F, Frank JS, Powell C, Zabjek KF. Unified theory regarding A/P and M/L balance in quiet stance. J Neurophysiol [Internet]. 1996 Jun 1 [cited 2021 Aug 23];75(6):2334–43. Available from: www.physiology.org/journal/jn

30. Bučková K, Lobotková J, Hirjaková Z, Bzdúšková D, Hlavačka F. Postural control assessed by limit of stability in obese adults. Act Nerv Super Rediviva. 2014;56(3–4).

31. Duarte M, Freitas SMSF. Revisão sobre posturografia baseada em plataforma de força para avaliação do equilíbrio. Rev Bras Fisioter [Internet]. 2010 Jun;14(3):183–92. Available from: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1413-35552010000300003&lng=pt&nrm=iso&tlng=pt

32. Penedo T, Polastri PF, Rodrigues ST, Santinelli FB, Costa E de C, Imaizumi LFI, et al. Motor strategy during postural control is not muscle fatigue joint-dependent, but muscle fatigue increases postural asymmetry. Woloschak GE,

editor. PLoS One [Internet]. 2021 Feb 25 [cited 2022 Jul 25];16(2):e0247395. Available from: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0247395

33. Mariève B, François P, Martin L, Sylvain C, Julie M. Maximal stability limits in adolescents with Tourette syndrome. J Adv Pediatr Child Heal [Internet]. 2021 Jan 30 [cited 2022 Jul 11];4(1):013–22. Available from: https://www.heighpubs.org/japch/japch-aid1024.php
34. da Silva W, Machado ÁS, Souza MA, Mello-Carpes PB, Carpes FP. Effect of green tea extract supplementation on exercise-induced delayed onset muscle soreness and muscular damage. Physiol Behav [Internet]. 2018 Oct;194:77–82. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0031938418302294
35. Kelly-Martin R, Doughty L, Garkavi M, Wasserman JB. Reliability of modified adheremeter and digital pressure algometer in measuring normal abdominal tissue and C-section scars. J Bodyw Mov Ther [Internet]. 2018 Oct [cited 2021 Sep 27];22(4):972–9. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1360859218300858
36. Cumming G. Cohen’s d needs to be readily interpretable: Comment on Shieh (2013). Behav Res Methods [Internet]. 2013 Dec 4;45(4):968–71. Available from: http://link.springer.com/10.3758/s13428-013-0392-4
37. Espirito Santo H, Daniel FB. Calcular e apresentar tamanhos do efeito em trabalhos científicos (1): As limitações do p < 0,05 na análise de diferenças de médias de dois grupos. Rev Port Investig Comport e Soc [Internet]. 2015 Feb 28;1(1):3–16. Available from: https://rpics.ismt.pt/index.php/ISMT/article/view/14

38. Nam HS, Park DS, Kim DH, Kang HJ, Lee DH, Lee SH, et al. The Relationship Between Muscle Fatigue and Balance in the Elderly. Ann Rehabil Med [Internet]. 2013;37(3):389. Available from: http://e-arm.org/journal/view.php?doi=10.5535/arm.2013.37.3.389

39. Buková A, Kováčiková Z, Sarvestan J, Neumannová K, Pecho J, Zemková E. Advancing age is associated with more impaired mediolateral balance control after step down task. Gait Posture [Internet]. 2023 Feb;100:165–70. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0966636222007287

40. Anguish B, Sandrey MA. Two 4-Week Balance-Training Programs for Chronic Ankle Instability. J Athl Train [Internet]. 2018 Jul 1;53(7):662–71. Available from: https://meridian.allenpress.com/jat/article/53/7/662/112522/Two-4Week-BalanceTraining-Programs-for-Chronic

41. da Rocha ES, Vaz MA. TRICEPS SURAE NEUROMECHANICAL PROPERTIES AFTER ACHILLES TENDON SURGICAL REPAIR: FROM REHABILITATION TO TRAINING. [Porto Alegre]: Universidade Federal do Rio Grande do Sul; 2020.

42. Maritz CA, Silbernagel KG. A Prospective Cohort Study on the Effect of a Balance Training Program, Including Calf Muscle Strengthening, in Community-Dwelling Older Adults. J Geriatr Phys Ther [Internet]. 2016 Jul;39(3):125–31. Available from: https://journals.lww.com/00139143-201607000-00005

43. Schrager MA, Kelly VE, Price R, Ferrucci L, Shumway-Cook A. The effects of age on medio-lateral stability during normal and narrow base walking. Gait Posture [Internet]. 2008 Oct;28(3):466–71. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0966636208000660

44. da Silva W, Machado ÁS, Lemos AL, de Andrade CF, Priego-Quesada JI, Carpes FP. Relationship between exercise-induced muscle soreness, pain thresholds, and skin temperature in men and women. J Therm Biol [Internet]. 2021 Aug 1 [cited 2021 Oct 5];100:103051. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0306456521002199
45. Haefeli M, Elfering A. Pain assessment. Eur Spine J. 2006 Jan;15(SUPPL. 1).
46. Vuillerme N, Sporbert C, Pinsault N. Postural adaptation to unilateral hip muscle fatigue during human bipedal standing. Gait Posture [Internet]. 2009 Jul [cited 2021 Jun 4];30(1):122–5. Available from: https://linkinghub.elsevier.com/retrieve/pii/S096663620900099X
47. Paillard T. Effects of general and local fatigue on postural control: A review. Neurosci Biobehav Rev [Internet]. 2012 Jan;36(1):162–76. Available from: http://dx.doi.org/10.1016/j.neubiorev.2011.05.009
48. Paillard T. Effects of general and local fatigue on postural control: A review. Vol. 36, Neuroscience and Biobehavioral Reviews. 2012. p. 162–76.
49. Jonsson E, Seiger Å, Hirschfeld H. One-leg stance in healthy young and elderly adults: a measure of postural steadiness? Clin Biomech [Internet]. 2004 Aug;19(7):688–94. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0268003304000737
50. Ting LH. Dimensional reduction in sensorimotor systems: a framework for understanding muscle coordination of posture. In: Progress in Brain Research [Internet]. 2007. p. 299–321. Available from: https://linkinghub.elsevier.com/retrieve/pii/S007961230665019X
51. Liew BXW, Del Vecchio A, Falla D. The influence of musculoskeletal pain disorders on muscle synergies—A systematic review. Jan Y-K, editor. PLoS

One [Internet]. 2018 Nov 5 [cited 2023 Jun 16];13(11):e0206885. Available from: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0206885

52. Palmieri-Smith RM, Kreinbrink J, Ashton-Miller JA, Wojtys EM. Quadriceps Inhibition Induced by an Experimental Knee Joint Effusion Affects Knee Joint Mechanics during a Single-Legged Drop Landing. Am J Sports Med [Internet]. 2007 Aug 30;35(8):1269–75. Available from: http://journals.sagepub.com/doi/10.1177/0363546506296417

53. Fransz DP, Huurnink A, de Boode VA, Kingma I, van Dieën JH. Time to stabilization in single leg drop jump landings: An examination of calculation methods and assessment of differences in sample rate, filter settings and trial length on outcome values. Gait Posture [Internet]. 2015 Jan 1 [cited 2022 Aug 1];41(1):63–9. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0966636214006821